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MAGNITUDE AND FREQUENCY OF DEBRIS FLOWS

PEGGY A. JOHNSON[1], RICHARD H. McCUEN[1] and THEODORE V. HROMADKA[2]

[1]*Department of Civil Engineering, University of Maryland, College Park, MD 20742 (U.S.A.)*
[2]*Applied Mathematics Department, California State University, Fullerton, CA 92643 (U.S.A.)*

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ABSTRACT

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Debris flows periodically result in the loss of lives and property. Engineering structures designed to control debris flows are often inadequate because of lack of knowledge of the magnitude of debris events. The objective of this study was to develop a method that could be used to estimate the magnitude and frequency of debris flows. The data base for the study included 29 watersheds in the Los Angeles area, with drainage areas < 3 mile^2. Assuming a log-normal distribution, prediction equations for 2-, 5-, 10-, 25-, 50-, and 100-year return periods were developed as a function of relief ratio, hypsometric index, the interval between burns, and drainage area. Principal components and correlation analyses were used to select the predictor variables. Numerical optimization was used to calibrate the model. The prediction equations can be used to estimate the magnitude of debris flows for ungaged watersheds where estimates are required for debris basin and channel design, protection of culverts and roads, land use planning, and zoning and establishing insurance rates.

INTRODUCTION

Periodically the news media report of voluminous mudflows that result in the loss of many lives as well as extensive property damage. Although mudflows have always occurred, very few data have been collected to document the magnitude and frequency of these events. Where attempts have been made to engineer structures to control mudflows, the design of control structures is often based on the volume of a previous mudflow at the site rather than on the basis of the potential magnitude of a future event. There is a need for regionalization of information pertaining to such events so that rational policies can be developed to control occurrences that can be expected in the future.

While the term 'mudflow' is used by the media, the term 'debris flow' will be used here. Both terms refer to the mass movement of soil and rock. While 'mudflow' often suggest flows consisting primarily of relatively small particles and 'debris flow' is used for flows containing a significant proportion of large rocks, there is no widely accepted, consistent system for classifying the wide array of mass movements of soils and rock. Dunne and Leopold (1978) separate the mass movements of soils into falls, slides, flows, and soil creep, with rockfalls as a subcategory of falls. Slides are separated into planar failures (rock slides, debris slides) and rotational failures (slumps). Flows are subdivided into debris avalanches, debris flows, earthflows, mudflows (including lahars), and solifluction. Unfortunately, a unique means for identifying which category an event belongs to does not exist. In fact, Costa and Jarrett (1981) reported confusion in classifying events as dissimilar as debris flows and waterflows.

To prevent the loss of life and property damage that result from debris flows, a number of engineering structures have been proposed. Hollingsworth and Kovacs (1981) discussed the following protection methods: retaining, deflection, and stem walls, debris basins, and debris fences. Debris racks, which can be installed immediately upstream of culverts, can be used to prevent drainage systems from being clogged by debris. In discussing the control of soil mass movement, Sidle et al. (1985) classify control measures as: (1) excavation and filling techniques; (2) drainage methods; (3) restraining structures; (4) miscellaneous methods (such as grouting and chemical stabilization). However, to protect life and property using structures, it is important to have estimates of the magnitude and frequency of such occurrences. Unfortunately, methods for estimating the magnitude and frequency of mass soil movements such as debris flows are not readily available.

Depending on the size of the watershed, the debris flow at a particular site results from failure along one or more slip surfaces. Each of these slip surfaces has a different geometry, depth, and slope, as well as soil/rock characteristics. Wieczorek (1987) reports three types of failure surfaces in the La Honda area of northern California. Different volumes of water are required to initiate a debris flow on each of these failure surfaces, depending on whether the slip surface is very shallow, shallow, or deep. The soil over a very shallow slip surface will require a relatively short duration of rainfall to reach saturation and thus initiate movement of the soil (Wieczorek, 1987). Therefore, the magnitude of successive debris flows will be highly varied, often by orders of magnitude. Existing slope stability models or groundwater fluxuation models cannot account for this variation in magnitude unless accompanied by an extensive data base.

The objective of this study was to develop a prediction method that could be used to estimate the magnitude and frequency of debris flows for areas where soils and well data do not exist or where slope stability methods cannot adequately predict magnitudes of debris resulting from the failure of multiple slopes. Procedures that are commonly used for the calibration of waterflood models were applied to debris flow data from Los Angeles County, CA.

PHYSICAL FACTORS CONTROLLING DEBRIS FLOWS

A first step in debris basin planning is to identify whether or not the potential exists for significant volumes of debris. Two general types of data should be studied, historical evidence of debris flows and characteristics related to the physical process of debris generation. Historical evidence should be examined for both the study watershed and regional watersheds having similar characteristics. If watersheds in the vicinity of the study watershed have similar characteristics and have experienced debris flows, then the potential for such flows on the study watershed should be given greater consideration; however, this is not a necessary condition. The absence of debris flows on adjacent watersheds does not preclude the occurrence of debris flows on the study watershed. However, past debris flows on the study watershed is a clear indication that debris-flow generation characteristics should be assessed.

On-site characteristics that should be considered in assessing the potential for debris flow can be generalized as hydrometeorological, topographic, soil, and burn potential. In addition to the duration and intensity of the storm that ultimately produces the debris flow, antecedent rainfall is an important meteorological characteristic. The antecedent storms saturate the soil and reduce the frictional resistance at the failure plane. The duration and volume of the storm that produces the debris failure are important because they are determining factors in the depth of surface runoff, which was shown by Takahashi et al. (1987) to be an important factor in debris flow hydrograph characteristics. The intensity–duration–frequency relationship for periods of up to 7 days should be considered. A severe, short-duration rainfall event may not be sufficient by itself to cause a debris flow.

The interaction of soil and topographic factors is also important. Based on Bagnold's limiting slope condition (1956), Takahashi et al. (1987) indicate that the critical slope θ_c for a debris flow is a function of the internal angle of friction ϕ, and both the weight density (ρ_s) and volume concentration of solids in the static bed (C):

$$\tan\theta_c = \frac{C(\rho_s - \rho)}{C(\rho_s - \rho) + 2\rho}\tan\phi \tag{1a}$$

where ρ is the density of water. Based on a generalized viscoplastic model of debris flow, Chen (1988) provided the following alternative to eqn. (1a):

$$\tan^{-1}[(\bar{\rho}\bar{\mu}/\rho)\sin\phi] < \theta < \tan^{-1}[(\bar{\rho}/\rho)(-\mu_1/\mu_2)] \tag{1b}$$

where: ρ is the bulk or mass density of the sediment–water mixture; ρ_w is the mass density of water; $\bar{\rho}$ is the difference $\rho - \rho_w$; μ_1 and μ_2 are the consistency and cross-consistency indices, respectively. When the surfaces of the overland flow and seepage are less than the critical value defined by eqn. (1a), then the bed should be stable. Sangrey et al. (1984) developed a method of predicting the recurrence interval of slope failure based on calculated groundwater levels and characteristics of the soil and aquifer. This method requires a well record, as well as site characteristics such as the slip surface location and soil properties. Unfortunately, these data are expensive and often impractical to collect and so are not available for many debris flow areas, especially for watersheds larger than 25–50 acres.

It is the interaction between the meteorological factors and the soil and topographic factors, which is specified by eqn. (1), that initiates and sustains the debris flow. Antecedent rainfall and the resulting runoff infiltrates into the bed, with the hydrostatic pressure being transmitted to the shear plane that separates a layer of the movable bed from the next lower layer or bedrock. The debris-generating storm runoff causes debris movement at both the surface and the shear plane. Surface debris is moved by the high velocity surface flows. The bed itself will begin to slide since the tangential stress is greater than the resisting stress. The total volume of debris may be constrained by the resisting force exerted by the downstream portion of the bed. Where the tangential or friction force of the downstream section is lessened by antecedent water, the mass will offer less frictional resistance and a major debris slide can result.

The fourth factor that is an important determinant of debris movement is the land cover of the watershed, with special concern shown when fire destroys the vegetative cover. The heat generated by the fire sears the surface, which then limits infiltration. Thus, the loss of the naturally rough cover and the decreased potential for infiltration cause significant increases in the volume and velocities of the runoff, which initiate rill erosion. The water that does infiltrate cannot transpire because of the lack of a vegetal cover, thus remaining in the soil profile and increasing the stress. The lack of a viable plant root system in the denuded watershed compounds the problem as the resistance to tangential shear is reduced. These changes to the soil profile can increase the rate of debris movement from the surface as well as increasing the tangential stresses along the shear plane.

AREA OF STUDY

Data for this study are from the Los Angeles area, California. The watersheds where debris flows initiate are located in the Santa Monica, San Gabriel, Verdugo, and Santa Susana Mountains. Elevations range from 500 to 3000 ft in the Santa Monica Mountains to 5000–9000 ft in the San Gabriel Mountains. The basins are underlain predominantly by slate, schist, sandstone, shale, and quartz diorite colluvium consisting of sand, gravel, and boulders with little clay. Rainfall is restricted almost entirely to the winter months, November–March. Various rainfall characteristics are given in Table 1. Cumulative amounts for rainfall prior to debris flow storms vary from a mean of 0.87 in for a 1-day antecedent rainfall to 4 in for a 7-day antecedent rainfall. Debris-producing precipitations ranged from 1.50 to 13.35 in over a 24-h period. Campbell (1975) found that debris flows usually occur when the seasonal antecedent rainfall reaches 10 in or more followed by a storm with an intensity of at least 0.25 in h^{-1}. The antecedent storm saturates the soil profile, with the debris-generating rainfall serving as the trigger to failure.

Debris flows commonly begin on slopes of 26–45° and deposition of the debris usually occurs on slopes of 0–18° (Campbell, 1975). The mean relief ratio for the Los Angeles data base is 1635 ft $mile^{-1}$ which corresponds to a slope of about

TABLE 1

Statistics for watershed characteristics

Variable	Mean	SD	Min.	Max.
Max. 24-h precipitation (in)	4.92	2.42	1.50	13.35
Max. 1-h precipitation (in)	0.91	0.46	0.30	2.20
1-day antecedent rainfall (in)	0.87	1.12	0	5.11
2-day antecedent rainfall (in)	2.15	2.41	0	9.19
7-day antecedent rainfall (in)	4.00	3.75	0	13.76
50-year, 24-h storm (in)	12.45	1.07	9.34	13.51
Area (mile^2)	0.44	0.40	0.02	2.77
Hypsometric index	0.43	0.09	0.29	0.61
Relief ratio (ft mile^{-1})	1635	583	454	2772
SCS curve number	60.96	5.75	40.00	65.00
Drainage density (mile mile^{-2})	12.39	4.68	6.58	32.10
Total stream length (miles)	5.18	5.21	0.33	24.27
Bifurcation ratio	3.95	2.04	1.00	11.00
Elongation ratio	0.60	0.13	0.28	0.93
Burn (years)	9.87	12.17	0.08	46.23
Debris yield (10^3 cy mile^{-2} year^{-1})	211	320	0.98	1619
Debris yield (10^3 cy year^{-1})	72	107	0.19	665

17°. The mean, standard deviation, and maximum and minimum values for the watershed characteristics are given in Table 1. The relief ratio is defined as the maximum basin relief (ft) divided by the longest horizontal distance of the basin measured parallel to the major stream (miles). The relief ratio indicates the overall steepness of the basin (Ritter, 1978). The hypsometric index is defined as the relative height at which a watershed may be divided into two equal ground surface areas by a given contour. For example, a watershed with minimum and maximum elevations of 2000 and 4000 ft respectively, has an hypsometric index of 0.5 if the area is equally divided at the 3000-ft contour line. If the area is equally divided at the 2500-ft contour, the hypsometric index is 0.25. The drainage density is the ratio of the total channel length to the drainage area. The elongation ratio is found by dividing the diameter of a circle, equal in area to that of the watershed, by the watershed length.

The time between significant watershed burns and debris events varied from about 1 month to over 46 years. The debris produced by these events varied from 187 to 665 000 yd^3 year^{-1}. These statistics are also given in Table 1.

Soil data and local geology were not included in the analysis for a number or reasons. First, for the size of the basins included in this study, there was as much variation in soil properties within watersheds as there was between watersheds. This would make it difficult for a soil parameter to appear significant in the analysis of the data. Second, although soil characteristics may be highly correlated to slope failure, it is very difficult to quantify those soil properties for an entire watershed consisting of numerous failure sites. In addition, even if the same soil properties exist over an entire watershed, the debris flows will be initiated at any number of sites, each with a different slope, geometry, and depth. Each of these sites require various water volumes for saturation to induce mass movement of the soil. Thus, the number of slope failures varies for each debris flow event, resulting in a wide variation in magnitude. However, these soil characteristics must be considered by engineers in the development of sites of up to 10 20 acres. The problem of not being able to incorporate local geology into the prediction methods is not unique to this analysis. Pack (1985) did not include geology as part of his analysis because extensive site-specific investigations would have been required.

ANALYSIS OF DEBRIS FLOW DATA

The volume of debris for a particular site may vary by orders of magnitude from one event to the next. This variation is difficult to model using slope failure analysis. A frequency analysis provides a method of estimating the expected volumes. A log-normal population was assumed to underlie the physical processes. The frequency curve for the Bailey debris basin, which is located at the base of Bailey Canyon in the central San Gabriel Mountains, is shown in Fig. 1. The debris flows ranged in magnitude from about 3000 to 76 500 yd^3. The sample sizes were inadequate for evaluating the third moment, so a three-parameter probability function, such as the log Pearson type 3 distribution could not be evaluated. Table 2 provides a summary of the statistics for each of the stations. The length of the data records varies from 1 to 43 years. However, the data were not recorded yearly. Each record

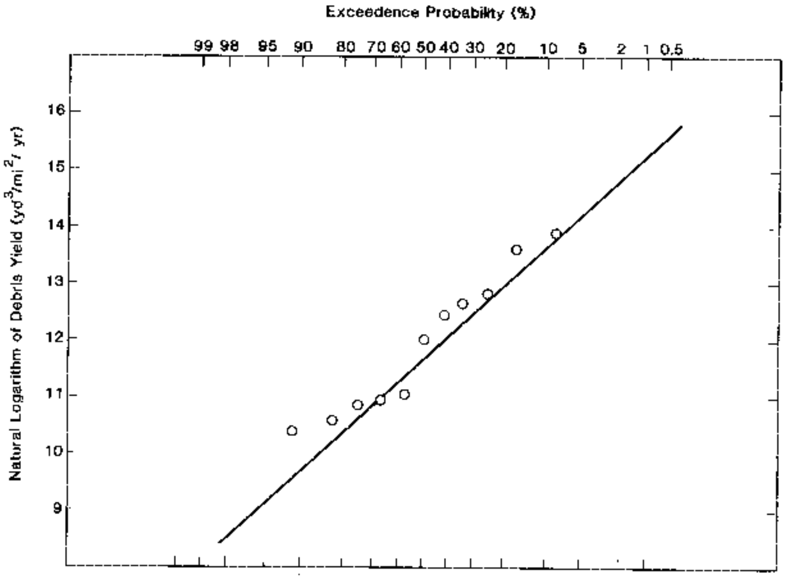

Fig. 1. Log-normal frequency distribution for the Bailey debris basin.

TABLE 2

Statistics of the yield for each of the stations

Debris basin	Years of record	Yield (10^3 cy mile $^{-2}$ year $^{-1}$)	Standard deviation ($\times 10^3$)
Auburn	15	539	450
Bailey	19	260	323
Blue Gum	12	179	244
Bradbury	13	102	71
Brand	15	83	52
Carriage House	1	432	675
Carter	21	250	404
Childs	17	70	117
Cloud Creek	5	186	293
Elmwood	17	103	96
Englewild	12	157	173
Fern	43	78	68
Harrow	12	198	265
Hay	40	32	23
Hook East	12	88	90
Kineloo West	12	212	294
Las Flores	27	80	52
Limekiln	15	28	27
Lincoln	43	54	59
Maddock	13	239	401
May	14	104	145
Morgan	14	23	15
Rubio	12	325	405
Snover	41	115	94
Sullivan	6	64	71
Ward	16	689	1185
Wildwood	15	82	90
Winery	12	52	26
Zachau	12	279	461

represents estimates of the debris volume that accumulated during some interval. For those basins with 40 or more years of record, there is a recorded debris flow in the 1930s and the next entry is not until the early 1960s. The yield (yd^3 mile^{-2} year^{-1}) was obtained by dividing the recorded yield by the area and by the interval length. The means and standard deviations were used with the log-normal distribution to compute the debris flow volumes in cubic yards per square mile per year for exceedence frequencies of 2, 5, 10, 25, 50, and 100 years. For each exceedence frequency, the derived debris flows were regressed on watershed characteristics. The following power model form was used:

$$Y = b_0 X_1^{b_1} X_2^{b_2} \dots X_p^{b_p} \tag{2}$$

where Y is the predicted debris flow for the specific exceedence frequency; X_i ($i = 1, 2, \dots, p$) is the value of the ith predictor variable; b_i ($i = 1, 2, \dots, p$) is the

ith standardized partial regression coefficient; and p is the number of predictor variables. Values for the regression coefficients were obtained using a procedure based on both ordinary least squares with a logarithmic transformation and numerical optimization (McCuen and Snyder, 1986). The ordinary least squares method was used to obtain approximate values for the regression coefficients. However, since ordinary least squares of the power model of eqn. (2) requires a logarithmic transformation of the volume of debris flow, y, the coefficients derived using ordinary least squares are biased and provide biased estimates of the criterion variable, debris flow (they provide unbiased estimates only in the logarithmic measurement space). To eliminate the bias and improve the standard error of estimate, the coefficients of eqn. (2) were further refined using a numerical algorithm. For this process, the ordinary least squares coefficients are used as initial estimates, but the numerical procedure does not require a logarithmic transformation of the data. Thus, the algorithm can provide an unbiased model by minimizing the sum of the squares of the errors in the y-space rather than in the log y-space. For most of the analyses, the ordinary least squares estimators were highly biased, so the numerically derived estimators were much more rational indicators of the effects of the predictor variables.

The number of predictor variables had to be reduced to ensure both rationality and practicality. When a model includes a large number of predictor variables, the coefficients of the non-dominant variables are often irrational. It is also not practical to require the measurement of unnecessary input data, such as for unimportant predictor variables. Thus, a subset of the predictor variables was selected based on a combination of principal components analysis, an assessment of the correlation matrix, an evaluation of the rationality of the numerically fitted coefficients of the power model, and our understanding of the relative importance of the variables in the physical processes. This is believed to be a better process than a computer-based selection, such as with stepwise regression (McCuen, 1985) and an arbitrarily selected level of statistical significance, for a number of reasons, not least of which is the fact that the stepwise procedure of the power model provides biased estimators.

The computed log-normal debris flows for the selected return periods, which are given in Table 3, were subjected to the optimization procedure outlined above. The watershed characteristics involved in the regression were the relief ratio, the elongation ratio, a hypsometric index, and the mean bifurcation ratio. Area, stream length, and drainage density were not used since area appears in the denominator of the criterion variable and stream length and drainage density reflect drainage size; including such variables would have resulted in spurious correlation (Pearson, 1932; Chayes, 1949). The regression of debris yield on these variables indicated that the bifurcation ratio was unimportant and that the coefficient for the elongation ratio was irrational. The relief ratio and hypsometric index, then, were selected as the watershed characteristics to predict the debris yield.

TABLE 3

Computed volumes of debris flows (10^3 cy mile^{-2} year^{-1}) for selected return periods

Debris basin	Return periods (years)					
	2	5	10	25	50	100
Auburn	539	918	1116	1327	1463	1586
Bailey	260	532	674	826	923	1011
Blue Gum	179	384	492	606	680	747
Bradbury	102	162	193	226	248	267
Brand	83	127	150	174	190	204
Carriage House	432	1000	1297	1614	1818	2002
Carter	250	590	768	957	1080	1190
Childs	70	168	220	257	310	342
Cloud Creek	186	433	562	699	788	868
Elmwood	103	184	226	271	300	326
Englewild	157	303	379	460	512	559
Fern	78	135	165	197	218	236
Harrow	198	421	538	662	742	814
Hay	32	51	61	72	79	85
Hook East	88	164	203	246	273	297
Kincloo West	212	459	589	727	816	896
Las Flores	80	124	147	171	187	201
Limekiln	28	51	63	75	83	91
Lincoln	54	104	130	157	175	191
Maddock	239	576	753	941	1063	1172
May	104	226	290	358	402	441
Morgan	23	36	42	49	54	58
Rubio	325	666	844	1034	1157	1267
Snover	115	194	236	280	308	334
Sullivan	64	124	155	188	210	229
Ward	689	1686	2208	2764	3123	3445
Wildwood	82	158	197	240	267	291
Winery	52	74	85	98	105	112
Zachau	279	667	870	1086	1226	1351

The relief ratio indicates the overall steepness of the watershed and is found by dividing the maximum relief (ft) by the longest horizontal distance of the basin measured parallel to the major stream (miles). The hypsometric index indicates how the slope is distributed within the watershed. It is defined as the relative height at which a watershed may be divided into two equal ground surface areas by a given contour. Given a relief ratio, the hypsometric index may vary, with a higher index more indicative of higher debris flows.

The resulting regression coefficients and standard errors of estimate are given in Table 4. Since the objective was to develop a series of prediction equations that could be used to make debris flow volume estimates at ungaged locations, the fitted coefficients, which were certainly influenced by sampling variation, were smoothed across exceedence frequencies; this is necessary to ensure rational prediction equations and is standard practice when developing

TABLE 4

Regression coefficients and standard errors of estimate for selected return periods

Return period (years)	b_0	b_1	b_2	Standard error of estimate ($\times 10^3$)	Standard deviation ($\times 10^3$)
2	300	0.711	0.141	44	47
5	908	0.826	0.196	305	319
10	383	1.039	0.205	650	710
25	574	1.129	0.372	1900	2000
50	551	1.218	0.387	3800	4000
100	734	1.268	0.498	7400	7700

equations for waterflow estimation. The coefficients were smoothed by plotting the coefficients on normal frequency paper and fitting a smooth curve across exceedence frequencies for each coefficient of eqn. (2).

DEVELOPMENT OF BURN FACTOR

The debris yield prediction equations were only a function of the watershed characteristics and did not specifically account for either the effect of burn or antecedent rainfall amounts. The equations were based on watershed characteristics that do not vary with time. They were developed with such data because the burn variable varied over the length of record, and regionalization with a univariate frequency analysis is not capable of handling a temporally varied data base. In order to determine the effect of burn, the debris yield was related to both the watershed characteristics and the interval since the most recent burn. The debris yield (in $yd^3\ year^{-1}$, rather than $yd^3\ mile^{-2}\ year^{-1}$) was regressed on 20 variables, including: drainage area; relief ratio; elongation ratio; drainage density; hypsometric index; total stream length; mean bifurcation ratio; maximum 1-, 3-, and 24-h storm precipitation amounts; watershed percent saturation; the 50-year, 24-h storm; Soil Conservation Service curve number; antecedent storm precipitation amounts; years since the most recent forest fire in which at least 40% of the watershed was burned.

A principal components analysis using the correlation matrix was performed to reduce the number of predictor variables. Kaiser's rule states that only eigenvalues > 1 are significant. Analysis of the eigenvalues, which are given in Table 5, showed that no more than seven of the 20 predictor variables were required. Using the seven eigenvectors that correspond to the seven significant eigenvalues, the eigenstructure was evaluated to select the seven variables. The seven most important predictor variables corresponding to the seven eigenvectors were the watershed area, relief ratio, percent watershed saturation, 24-h, 50-year storm, years since burn, 2-day antecedent rainfall, and drainage density. The debris yield was regressed on these seven variables. The

TABLE 5

Eigenstructure from principal components analysis

Factor	Eigenvalue	Percent trace	Cumulative percent	Degrees of freedom	χ^2 statistic for sphericity test
1	4.82	24.1	24.1	190	1389.77
2	3.87	19.4	43.5	171	1253.08
3	2.42	12.1	55.6	153	1117.65
4	1.91	9.6	65.1	136	1026.54
5	1.58	7.9	73.0	120	944.30
6	1.19	5.9	79.0	105	864.88
7	1.09	5.4	84.4	91	798.34

Variables	Eigenvectors						
	1	2	3	4	5	6	7
Max. 24-h amount	0.79	0.15	-0.41	0.15	-0.03	0.04	0.00
Max. 3-h amount	0.83	0.08	-0.38	0.06	-0.31	0.07	0.00
Max. 1-h amount	0.74	0.09	-0.40	-0.07	-0.41	0.03	-0.03
Percent saturation	0.24	0.30	0.07	0.63	0.32	0.17	-0.27
Watershed area	0.44	-0.73	-0.38	0.15	-0.02	-0.23	0.16
50-year, 24-h storm	0.59	0.21	0.14	-0.14	-0.45	-0.27	-0.33
SCS curve number	0.35	0.11	-0.14	-0.56	0.53	-0.11	0.30
1 + 1-day antecedent storm	0.22	-0.54	0.55	0.10	0.12	-0.15	-0.32
1 + 2-day antecedent storm	0.64	-0.66	0.27	0.06	0.13	0.05	0.02
1 + 3-day antecedent storm	0.72	-0.60	0.11	0.06	0.14	0.17	0.14
1 + 7-day antecedent storm	0.72	-0.55	0.06	0.05	0.17	0.22	0.12
Years since burn	0.17	0.01	-0.43	0.43	0.42	-0.33	-0.35
Relief ratio	0.39	0.43	0.50	0.30	-0.01	-0.05	0.30
Elongation ratio	-0.09	0.08	0.25	0.67	-0.45	-0.33	0.18
Drainage density	0.51	0.51	0.21	0.02	0.22	-0.29	0.38
Hypsometric index	0.39	-0.23	0.14	0.19	-0.21	0.64	0.16
Total stream length	-0.35	-0.68	0.37	0.17	0.04	-0.34	0.29
Bifurcation ratio	-0.05	-0.41	0.39	-0.36	-0.06	0.05	-0.25
Years since last stream	-0.01	0.34	-0.71	0.29	0.05	0.22	0.19
Debris yield	0.11	-0.73	0.01	0.32	-0.40	-0.16	0.24

standardized partial regression coefficients for the drainage density, relief ratio, and the 24-h, 50-year storm were low, showing that these variables contributed relatively little to the model. A negative partial regression coefficient for the percent watershed saturation was not used as a predictor variable in the final model. Using a power model having the form of eqn. (2), the debris yield was regressed on the three remaining variables: area, 2-day antecedent rainfall, and years since burn. Using the resulting regression coefficients as initial estimates, the standard error of estimate and bias were then reduced by numerical optimization. The resulting equation showed that the burn interval had an exponent of -0.24. For the Los Angeles data base the values for the years since burn interval ranged from 0.08 to 46 years, giving a mean change in debris yield of about 5 times over the entire range. This is in agreement with increased yield reported by Helvey (1980) and Sidle et al. (1985).

The coefficient describing the relative effects of the years since the watershed burned was incorporated into the six debris yield equations in order to account for the effect of burn. The mean time interval between burns for the data base was 9.87 years. The residuals from the numerical optimization output were examined to determine whether the effect of a watershed burn varied with the return period. There was no evidence to support a varying effect, so the effect of burn was assumed to be constant across the return periods. From the regression model, the burn factor is equal to the burn interval (years) raised to the -0.24 power. The prediction equations including the effect of burn are:

$$Y_2 = 485B^{0.24} R^{0.75} \mathrm{H}^{0.11} \tag{3}$$

$$Y_5 = 675B^{-0.24} R^{0.93} H^{0.19} \tag{4}$$

$$Y_{10} = 795B^{-0.24} R^{1.03} H^{0.26} \tag{5}$$

$$Y_{25} = 940B^{-0.24} R^{1.13} H^{0.35} \tag{6}$$

$$Y_{50} = 1080B^{0.24} R^{1.20} H^{0.42} \tag{7}$$

$$Y_{100} = 1225B^{0.24} R^{1.26} H^{0.48} \tag{8}$$

where: B is the number of years since the most recent burn in which at least 40% of the vegetated area of the watershed burned; R is the relief ratio (ft mile^{-1}); H is the value of the hypsometric index; Y_i is the magnitude of the debris flow for a return period of i years (yd^3 mile ^{2} year ^{1}).

When using eqns. (3)–(8), it is important to understand the characteristics of the data available for their calibration. Table 1 includes summary statistics of the data base. The drainage area is of special note. The mean area was 0.44 mile^2 or 281 acres. For such watersheds, significant volumes of debris are generated from more than one failure surface. This makes it difficult to include predictor variables that relate to characteristics of individual failure surfaces. It is also important to note that the equation did not include variables representing either rainfall or soil/rock characteristics. As discussed above, both of these variables are important in predicting failure for a site. However, in predicting magnitudes for an entire watershed consisting of numerous failure sites, the watershed characteristics may be used. The regression coefficients of eqns. (3) (8) reflect both the rainfall and soil/rock characteristics, and before these equations are used in any area outside southern California an analysis of their applicability, including soil and rock type, should certainly be undertaken.

DISCUSSION AND CONCLUSIONS

Debris flows present a hazard to life and property. Estimates of the volumes of debris flows are necessary if mitigating measures are to be taken. Debris basins are common engineering structures that are used to control debris flows as they flow from canyons onto alluvial fans. The expected volumes of debris flows are a necessary input to the design. The frequency of occurrence of such volumes is a necessary input for economic impact studies. Estimates of the volumes of debris flows are also important for delineating flow profiles for debris-flows, establishing insurance rates, locating and sizing other engineering structures such as highways, culverts, and bridges, and establishing land development and zoning policies.

Equations were developed for the estimation of the magnitude and frequency of debris flows for the Los Angeles area. The equations are a function of watershed characteristics (relief ratio and hypsometric index) and the burn interval. Other factors such as rainfall amounts are implicit in the coefficients, which vary with the return period. Equations are provided for return periods of 2, 5, 10, 25, 50, and 100 years. The volumes computed by the equations may be used as estimates of the volumes of debris that can be expected for a watershed. However, variations in soils, geologic setting, vegetation, and groundwater levels should be considered for each individual site if the equations are to be used for mitigation measures. The occurrence of a major burn just prior to a debris-generating storm can increase the volume of a debris flow by a factor of about 5.

The index flood method is commonly used in waterflood planning because of its simplicity. To use this method, the discharge is computed for the index flood, which is frequently the 2-year discharge, with a regression equation and then discharges can be computed for other return periods using a set of multiplication constants called index ratios. Equations (3)–(8) can be used to derive debris-flow index ratios for planning purposes. The 2-year event is used as the index flow. Using the mean values of the predictor variables, the index ratios were computed and found to be approximately equal to the return period for return periods up to the 50-year event. For example, the 25-year debris flow was approximately 25 times greater than the 2-year debris flow. The 100-year debris flow is approximately 80 times the 2-year debris flow. These index ratios should only be used for planning purposes. Index ratios for waterfloods are typically between 1.5 and 5.0. The ratios for debris flows are much higher, ranging from 5 to 80. This difference may be due to several factors. The index ratios for waterfloods represent an instantaneous peak discharge, whereas the ratios for debris flows represent a total volume of debris generated by rainfall lasting 7 days or longer. This volume includes the water from the storm plus the eroded sediment.

Equations (3)–(8) may be used to provide estimates of seasonal debris flow volumes in $\mathrm{yd}^3\ \mathrm{mile}^{-2}\ \mathrm{year}^{-1}$. The expected volume of debris is found by multiplying the estimate by the drainage area (mile^2) and by a time duration, which would be the interval over which rainfall occurs when debris flows are generated. This period might be of the order of 3–6 months.

The volumes computed by this method predict the debris flow and may be useful for engineering, planning, and policy purposes. Rather than basing a debris basin design on the volume of a previous debris flow, a policy for debris flow return and burn interval could be established and the appropriate prediction equation used to compute the expected volume of storage necessary. The prediction equations may aid in the design and location of flood channels, outflow culverts, roads, and other engineering structures. Local governments may also wish to use the predicted debris flow volume as a guide in land use planning and in determining areas that are inappropriate for housing development. The prediction equations may be used to establish rates of liability insurance for the jurisdiction, as well as for household insurance.

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